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RAISED-FLOOR DATA CENTER: PERFORATED TILE FLOW RATES FOR VARIOUS TILE LAYOUTS

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ABSTRACT

This paper summarizes the results of an experimental study of airflow rates through perforated tiles in a raised-floor data center. Flow rates are presented for various configurations of perforated tiles under different scenarios for the computer room air conditioning (CRAC) units. The measured airflow rates for selected cases are compared with those given by a computational fluid dynamics (CFD) program. The two sets of results are in good agreement.

KEY WORDS: Raised-floor data center, Airflow distribution, Computational Fluid Dynamics, Airflow model.

INTRODUCTION

The heat dissipated by electronic equipment is increasing at a very rapid rate. The data on heat dissipation rates for a variety of computer equipment has been compiled by a consortium of 17 manufacturers and published by the Uptime Institute [1]. It shows that the heat flux of rack level servers and storage equipment has doubled over the past five years. In the year 2003, the maximum heat flux for such servers was 15,000 W/m^2, which translates into a heat load of 22,000 W for a 19-inch rack. Cooling of such high-heat-load racks distributed in a data center is a serious challenge facing the facilities engineers.

A large majority of data centers use the raised-floor system to supply cooling air to the server racks. A necessary condition for good thermal management is to supply the required airflow through the perforated tile(s) located near the inlet of each computer server. The heat load can vary significantly across the computer room, and it changes with the addition or reconfiguration of hardware. For all computer servers to operate reliably, the data center design must ensure that the cooling air distributes properly; that is, the distribution of airflow rates through perforated tiles meets the cooling air needs of the equipment on the raised floor. Thus, an understanding of the airflow distribution is critical for designing effective data centers. Airflow distribution in raised-floor data centers is the topic of the present paper.

This paper makes two important contributions. First, it presents measured airflow rates for a number of floor layouts for raised-floor data-centers. This data highlights how the airflow distribution is affected by the arrangement of perforated tiles, the number of CRAC units and their locations, and the presence of turning vanes (scoops) on the CRAC units. To authors' knowledge this is the first time such data has been collected from a carefully controlled experiment. Second, it employs a computational tool for calculating the airflow rates and shows examples of the comparisons of the calculated airflow rates with the experimental data.

THE EXPERIMENTAL SETUP

In 2001, a raised-floor data center in the IBM plant in Poughkeepsie, New York, was about to be decommissioned, renovated, and turned into an office space. This presented an ideal opportunity for setting up a facility for measuring the airflow rates through perforated tiles. The raised floor area was large, measuring 24 m × 60 m, with 16 CRAC units placed in two parallel rows along the length of the room. It was felt that a small area would be sufficient to demonstrate the basic concepts, so a 6.06 m × 20 m section, shown in Fig. 1, was chosen for the experimental study. The raised floor height was 29.2 cm. The floor tiles were 610 mm (2 ft) on a side.

The positions of the CRAC units are shown in the top view included in Fig. 1. The CRAC units were positioned such that the airstreams exhausting from two units were directed toward each other; that is, the airstreams collided in a region between the units. However, for some of the runs, a scoop was mounted on CRAC unit A (the unit to the left in Fig. 1) such that the air was directed in the opposite direction. The effect of the scoop will be highlighted in the results section.

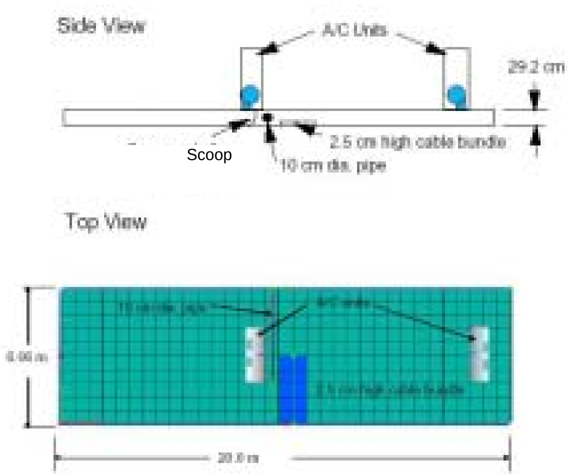

Figure 1. Raised Floor Test Layout

Since this was once an operating raised floor, some blockages were present underneath the floor. The major blockages were a 10-cm diameter pipe in front of the CRAC unit A, at the midpoint height between the raised floor and the subfloor, and a cable bundle, 1.2 m wide and 2.5 cm tall. These are shown in Fig. 1.

The test area was carefully sealed with cardboard and duct tape. Further, electrical or plumbing openings in this area were also sealed. These measures were necessary to ensure that all the air delivered by the CRAC units was exiting from the perforated tiles.

The CRAC units were Liebert model FH411C. These units were approximately 20-ton units and provided airflow rates of approximately 347 m^3/min. After detailed examination of the CRAC units it was found that the outlet openings of the units were partially blocked by solid floor tiles. As a result, the actual flow rate delivered by the units was less than the rated value. This reduction in the flow rate was taken into account when performing the CFD calculations.

The rated open area of perforated tiles is 25%. Actual measurements, however, showed that the open area is only 19.5%. The flow resistance of the perforated tiles was measured on a flow bench and is given by the following expression:

$$\Delta p(\text{in wg}) = 4.05 \times 10^{-7} Q(\text{cfm})^{1.99}$$

Figure 2 shows the six perforated-tile arrangements considered in this study. Each tile arrangement was chosen such that it could potentially support an array of racks aligned with the perforated tiles. The cold air from the perforated tiles washes the fronts of the racks, is drawn into the racks to cool the electronics, and is finally discharged from the rear of the racks to return to the inlets of the CRAC units.

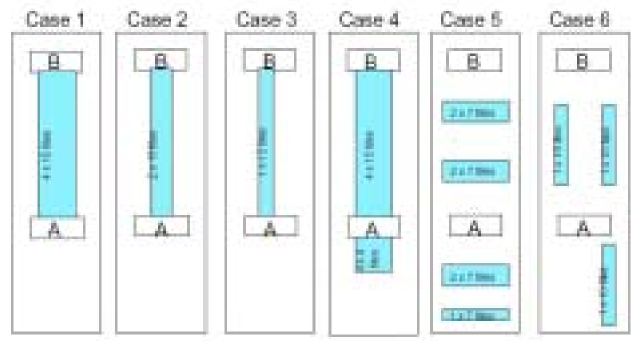

Figure 2. Tile Arrangements for the Test Cases

The airflow rates were measured with a calibrated Alnor balometer. This tool is capable of measuring flow rates from individual perforated tiles. The instrument was calibrated on a flow bench, and the collected data was suitably adjusted to account for the measurement errors. The total error in measurements, including instrument errors, is estimated to be within 5%.

EXPERIMENTAL RESULTS

Case 1 (Figures 3–5)

This configuration involves a 4 × 15 array of perforated tiles placed between two CRAC units. Figure 3 shows the flow rates with both CRAC units operating and turning vane (scoop) mounted on CRAC unit A (See Fig. 1). The flow rates for the tiles in the first two columns next to CRAC unit B are negative; that is, there is reverse flow into the plenum through these tiles. The reverse flow is caused by the negative plenum pressure (pressure less than the ambient pressure above the raised floor) resulting from the large velocities next to this CRAC unit. Farther away from the unit, the velocities diminish and the pressures and the airflow rates become positive. The flow rates are largest for the tiles near CRAC unit A. The slight dip for tiles in columns 5 and 6 is attributed to the presence of obstructions.

To study the effect of scoop on the airflow distribution, additional measurements were made with the scoop on Unit A removed. In this arrangement, the airstreams from the two CRAC units collide near the center of the perforated tile region. The airflow rates are shown in Fig. 4. Now the flow rates are small near the CRAC units and increase away from the units. The peak flow rate occurs near unit A. There is reverse flow through the perforated tiles next to the CRAC units; it is, however, milder than that seen with scoop on CRAC unit A. A comparison of airflow distribution with and without the scoop on CRAC unit A shows that the presence of the scoop leads to a better flow distribution over a larger region of the perforated tiles. Thus, installing the scoop may allow a larger number of racks.

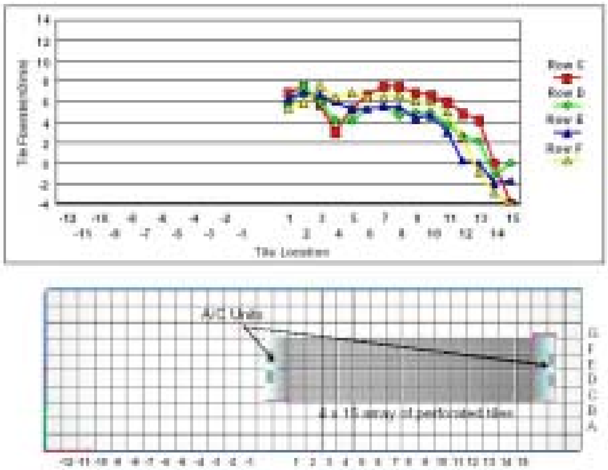

Figure 3. Case Study 1: Both CRAC Units Operating (Outward Scoop on CRAC Unit A)

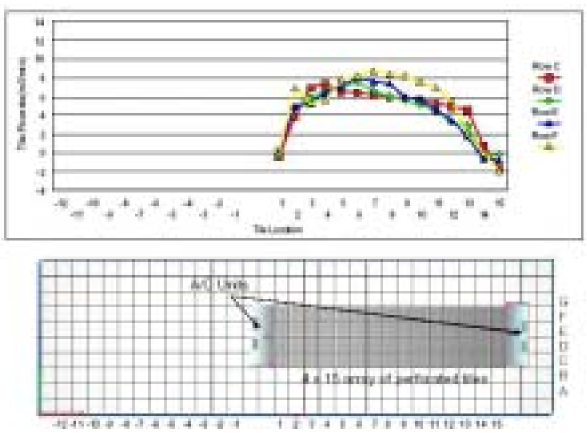

Figure 4. Case Study 1: Both CRAC Units Operating (Scoop Removed from CRAC Unit A)

For the results presented in the subsequent sections, CRAC unit A does not have the scoop, unless explicitly stated otherwise.

Figure 5 shows the flow rates when CRAC unit A (marked by an ×) is turned off and a cardboard piece is placed at the inlet of the unit to prevent backflow of air. (This test was also conducted without the cardboard piece. The total flow rates for the two situations differed by less than 1.2%.) With only CRAC unit B in operation, there is reverse flow through the first three columns of tiles next to this unit. The flow rates increase monotonically towards CRAC unit A, which is turned off.

Case 2 (Figures 6 and 7)

This case involves a 2 × 15 array of tiles between two CRAC units. Figures 6 and 7 show the flow rates with both CRAC units in operation and with CRAC unit A turned off, respectively. These results are qualitatively similar to those for

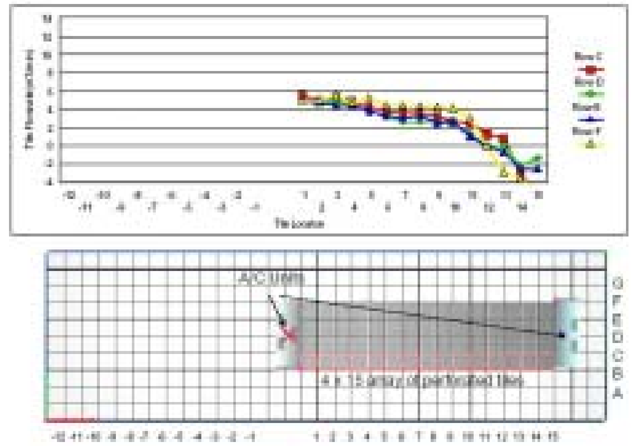

Figure 5. Case Study 1: CRAC Unit A Off/CRAC Unit B Operating

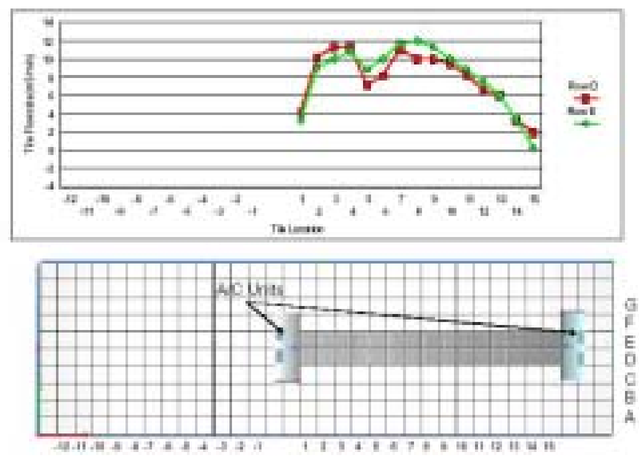

Figure 6. Case Study 2: Both CRAC Units Operating

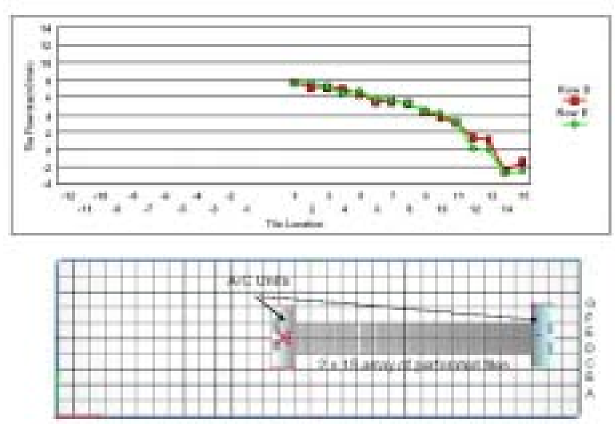

Figure 7. Case Study 2: CRAC Unit A Off/CRAC Unit B Operating

the 4 × 15 array of tiles, shown in Figs. 4 and 5. As expected, in the present configuration, the flow rates for individual tiles are larger.

For this case, the tendency for reverse flow through the perforated tiles next to the CRAC units is reduced compared to that in Case 1 (4 × 15 array of tiles). This result can be explained as follows: For the present configuration, flow rate per tile is larger, which requires a larger pressure drop across the tiles. Consequently, the pressure levels in the plenum are higher, and the pressure variations in the plenum are less prominent relative to the pressure drop across the tiles. Thus, the pressures within the plenum are mostly positive.

Case 3 (Figures 8 and 9)
This configuration involves a 1 × 15 array perforated tiles. Figure 8 shows the results when both CRAC units are in operation. Qualitatively, the airflow distributions are similar to those for Case 1 (4 × 15 array) and Case 1 (2 × 15 array). However, in the present configuration, all flow rates are positive. As explained earlier, a reduction in the number of perforated tiles increases the pressure levels in the plenum and makes the pressure distribution more uniform. For the present configuration, the pressures throughout the plenum are positive.

Figure 9 shows the results with CRAC unit A turned off. Again the airflow distributions are similar to those for the previous two configurations. However, the reverse flow is now confined to just one tile next to CRAC unit B and its magnitude is much smaller.

Case 4 (Figures 10 and 11)
This configuration involves a 4 × 15 array of perforated tiles (identical to that in Case 1) plus another 4 × 4 array of tiles to the left of CRAC unit A. Figure 10 shows the flow rates when the scoop is installed on CRAC unit A. The scoop is positioned such that the flow from CRAC unit A is discharged in the same direction as that from unit B. The flow rate distribution is nearly uniform for the tiles in the 4 × 4 array as well as for the tiles in the left half of the 4 × 15 array. The flow rates decrease as CRAC unit B is approached.

Figure 11 shows the airflow rates when the scoop is removed from CRAC unit A. Now, for both sets of tiles, the flow rates are small near the CRAC units and increase away from the units.

Case 5 (Figures 12 and 13)
This case involves three 6 × 2 and one 6 × 1 arrays of perforated tiles, all oriented parallel to the CRAC units. The airflow rates with both CRAC units in operation are shown in Fig. 12. For this condition, the perforated tiles between the two CRAC have significantly larger flow rates than those to the left of CRAC unit A.

Figure 13 shows the flow rates when CRAC unit A is turned off. The flow rates are negative for the perforated tiles close to

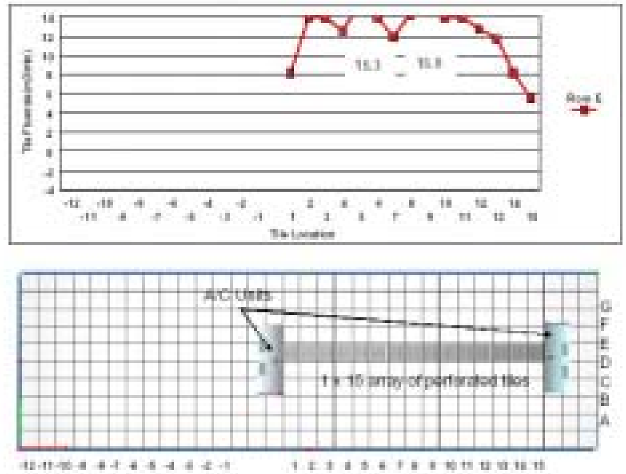

Figure 8. Case Study 3: Both CRAC Units Operating

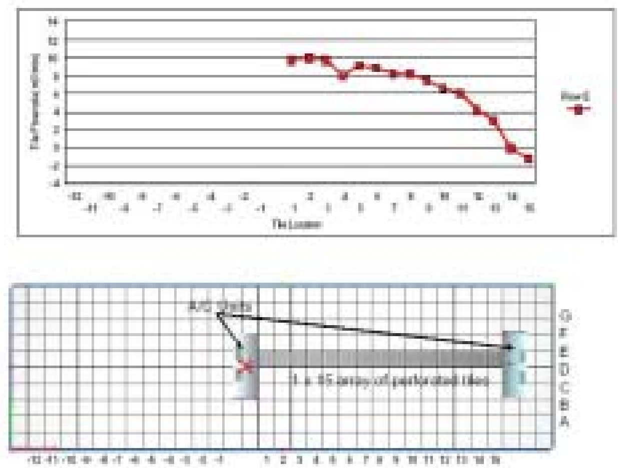

Figure 9. Case Study 3: CRAC Unit A Off/CRAC Unit B Operating

CRAC unit B, which is in operation; the flow rates are nearly identical for the remaining set of tiles.

Case 6 (Figures 14–16)
This configuration involves three isolated rows of perforated tiles. Figure 14 shows the results with both CRAC units in operation. The flow rates are generally larger for the tiles located between the two CRAC units. Figure 15 depicts the airflow distributions with CRAC unit A turned off. The flow rates are nearly the same for all perforated tiles, except for those next to CRAC unit B, which is in operation. Figure 16 depicts the flow distribution with CRAC unit B turned off. Flow rates are larger for perforated tiles close to CRAC unit B. There is reverse flow through all perforated tiles to the left of CRAC unit A.

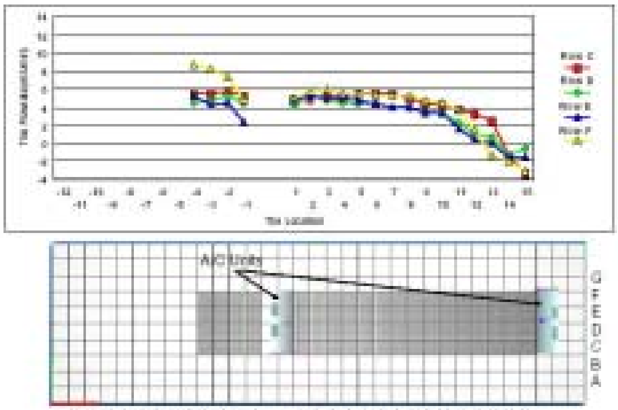

Figure 10. Case Study 4: Both CRAC Units Operating (Outward Scoop on Unit A Installed)

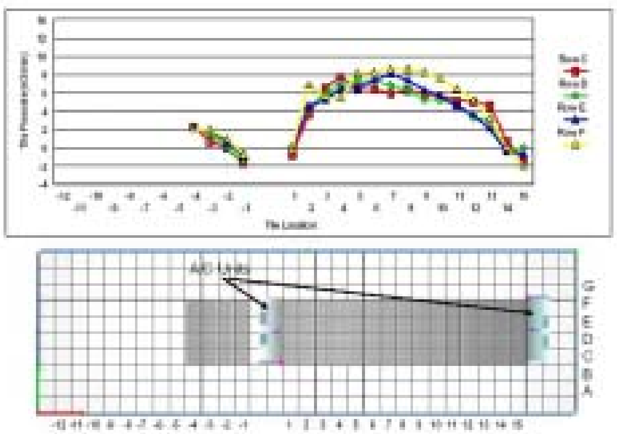

Figure 11. Case Study 4: Both CRAC Units Operating (Scoop Removed from Unit A)

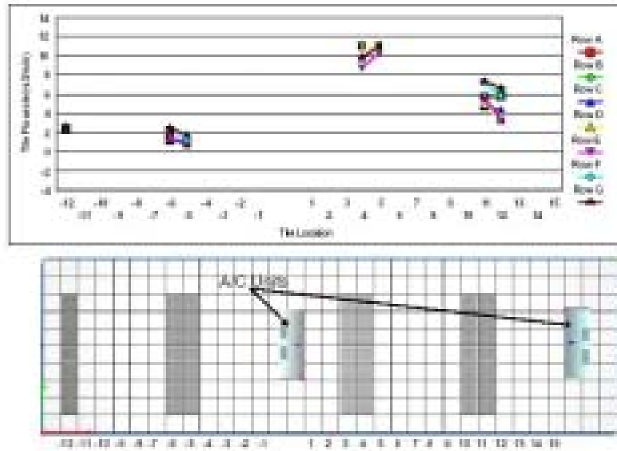

Figure 12. Case Study 5: Both CRAC Units Operating

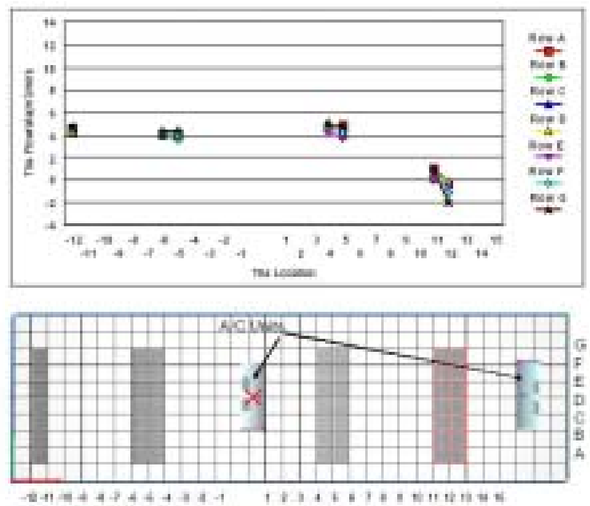

Figure 13. Case Study 5: CRAC Unit A Off/CRAC Unit B Operating

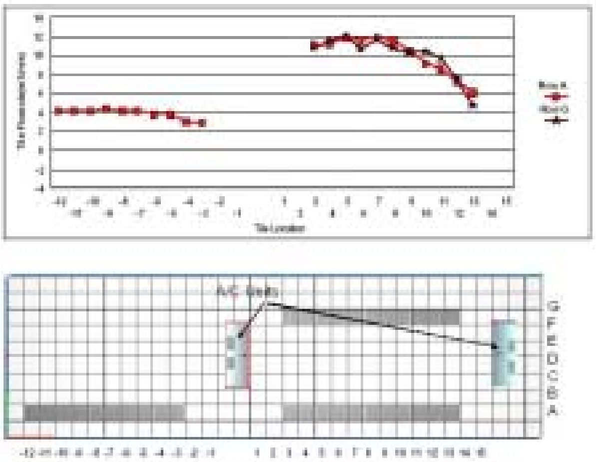

Figure 14. Case Study 6: Both CRAC Units Operating

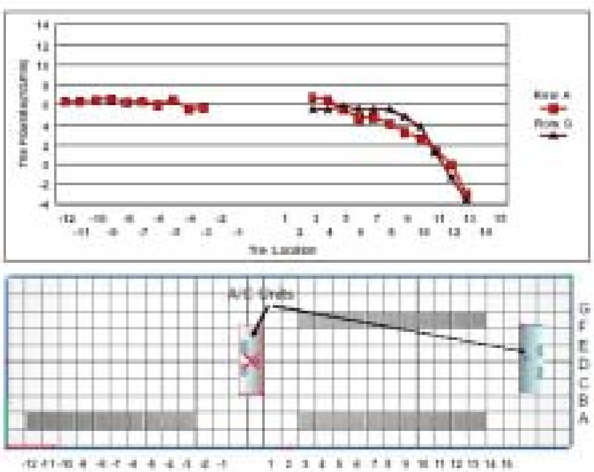

Figure 15. Case Study 6: CRAC Unit A Off/CRAC Unit B Operating

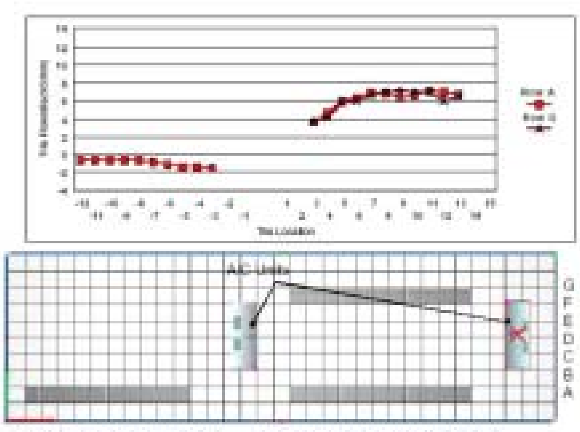

Figure 16. Case Study 6: CRAC Unit B Off/CRAC Unit A Operating

DEVELOPMENT OF A CUSTOMIZED COMPTUTATIONAL MODEL

The results presented in the preceding sections clearly show that the airflow distribution, even for a simple configuration, is a complex function of the layout of the perforated tiles and the positions of the CRAC units. In a real-life data center, it will depend on additional parameters related to the dimensions of the plenum, the open area of the perforated tiles, and the flow resistance/blockage of the obstructions like pipes and cables in the plenum. A clear understanding of the relationship between the airflow distribution and the governing parameters is essential for achieving the desired airflow distribution. The most convenient approach for establishing this relationship is through mathematical (computational) modeling.

For a computational model to be useful as a practical tool for designing new data centers and rearranging and retrofitting existing data centers, it must meet two criteria: (a) it should be easy to use (it should not require specialized knowledge of computational methods), and (b) it should produce results in short turnaround times. Of course, it should produce results that agree well with the experimental data.

Basis of the Computational Model

At first glance, it appears that the prediction of the airflow distribution would require calculation of velocity and pressure distributions in the plenum and in the computer room above the raised floor. This approach would involve a three-dimensional CFD model of the entire space. Such a model for a real-life data center would be time-consuming and cumbersome to build and would require very large run times. Fortunately, it turns out that such a complex model is not necessary.

The airflow rate through a perforated tile depends on the local pressure drop across the tile (pressure in the plenum minus pressure above the raised floor). The pressure variations above the raised floor are small compared to the pressure drop across the perforated tiles and can thus be ignored; that is, the pressure above the raised floor can be assumed uniform. As a result, the airflow distribution is governed primarily by the pressure distribution in the plenum and can, therefore, be obtained simply by solving the fluid flow equations in the plenum, subject to the condition of uniform pressure above the raised floor. The plenum-based model is considerably more efficient than a model that covers the entire data center (plenum plus the space above the raised floor).

Evolution of the Computational Model

The first attempt to predict the airflow rates through perforated tiles was reported by Kang et al. [2]. This paper presented a CFD model of a simple, idealized data center. The results showed a nearly uniform pressure in the plenum. Guided by this behavior, a network model that assumed a uniform plenum pressure was proposed. Note that the assumption of uniform plenum pressure eliminates the need for detailed calculation of velocity and pressure fields in the plenum. The results from this network model agreed well with the detailed results from the CFD model.

The assumption of uniform plenum pressure, however, is very restrictive and is appropriate only if the pressure drop across the tiles is much larger than the horizontal pressure variations within the plenum. This condition is satisfied if the total open area of the perforated tiles is comparable to or smaller than the frontal area (area normal to the predominant flow direction) under the raised floor. Otherwise, the horizontal air velocities under the raised floor become significant and introduce pressure variations in the plenum that are comparable to the pressure drop across the tiles. Thus, for a model to have universal applicability, it must include the calculation of flow field in the plenum.

The first plenum-based CFD model was reported by Schmidt et al. [3]. This model solved the two-dimensional (2D), or depth-averaged, flow equations. The 2D model is derived by integrating the three-dimensional form of the equations over the height of the plenum. The effect of turbulence was represented via an eddy viscosity model. The 2D model was used to calculate airflow rates in a small data center; the predicted airflow rates agreed well with the measured values. The depth-averaged model is appropriate if the variations along the plenum height are relatively unimportant. This condition can, however, be satisfied only if the plenum height is small (say < 0.30 m). For larger plenum heights, the flow details along the plenum height become important and must be calculated; this requires a three-dimensional (3D) model.

Karki et al. [4] have presented the details of a 3D plenum-based model for calculating the airflow rates through the perforated tiles. In this model, the governing equations are discretized using the finite-volume technique [5]. The coupled continuity and momentum equations are solved using a multigrid method [6]. The turbulence effects are represented via the k-ε model [7], which involves solution of additional partial differential equations for the turbulence kinetic energy and its rate of dissipation. The 3D model has been applied to many real-life data centers, and the flow rates through the perforated tiles are shown to be in good agreement with the measured values; representative results are available in the article by Karki et al. [4]. In a recent study, Guggari et al. [8] have shown that the results, for a prototype data center, from this plenum-based model are in excellent agreement with those given by a model that includes the entire data center in the calculation domain.

COMPARISON WITH CFD RESULTS

In this section, the measured airflow rates for two scenarios, which are variants of Case 1 (4 × 15 array of tiles) discussed earlier, are compared with the results from the CFD model of Karki et al. [4]. In Scenario 1, CRAC unit A is turned off. In Scenario 2, both CRAC units are in operation and there is no scoop on unit A.

Scenario 1 (Figures 17a and 18)

In this scenario, CRAC unit A is off. The test data, Fig. 5, shows reverse flow near unit B. Figure 17a shows the comparison of measured and predicted flow rates along one row of perforated tiles. The two sets of results are in good agreement. Figure 18 shows the predicted velocity vectors and pressure distribution under the raised floor. A large portion of the flow from the CRAC unit B exits as a jet directed toward unit A. The remaining fluid impinges on the right wall, turns around, and then exits from the perforated tiles. The longitudinal velocities (directed along the length of the plenum) are largest near unit B, producing negative plenum pressures, which lead to reverse flow. As expected, pressure is higher near the outlet of the CRAC unit B and within the stagnation point region on the right wall.

Scenario 2 (Figures 17b and 19)

In this scenario, both CRAC units are in operation. The test data shows reverse back flow near unit B (Figure 3). Figure 17b shows the comparison of predicted and measured flow rates. The predicted flow rates are in fair agreement with the measured values. Figure 19 shows the predicted velocity vectors and pressure distribution just under the raised floor. The flow exiting the CRAC unit A splits into two streams: one moving in the forward direction (toward unit B) and the other in the reverse direction. The stream flowing in the reverse direction impinges on the left wall, turns 180 deg., and then exits through the perforated tiles. Most of the fluid exiting the unit B is discharged as a jet towards unit A. A small amount of fluid impinges on the right wall. The longitudinal velocities (directed along the length of the plenum) are larger near unit B, causing large pressure variation in this region. The peak in the airflow velocity distribution is located closer to unit A and corresponds to the location where the two opposing streams meet.

CONCLUDING REMARKS

Airflow distributions are presented for a number of raised-floor data center configurations. Some key conclusions from this study are as follows:

- The airflow distribution is a strong function of the number of CRAC units in operation.
- An improved airflow distribution is achieved when both CRAC units discharge air in the same direction.
- The airflow distribution is more nonuniform when the CRAC units are oriented such that they discharge in opposing directions and their airstreams collide.
- There is reverse flow (flow into the plenum) through the perforated tiles close to the CRAC units in operation. The extent of reverse flow diminishes as the number of perforated tiles is reduced.
- The results from a CFD program are in good agreement with the experimental data.

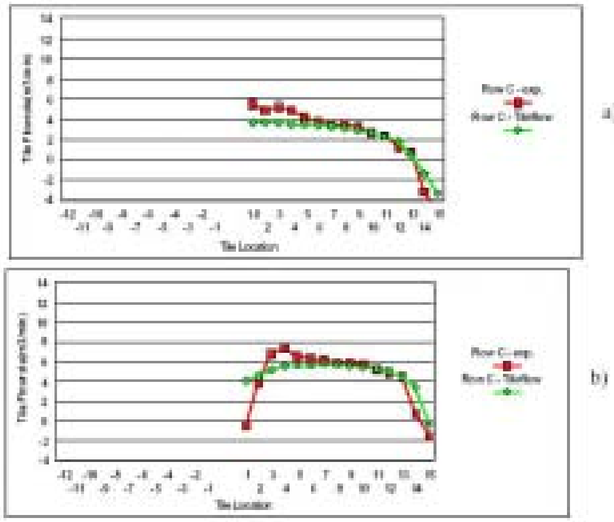

Figure 17. Comparison of Flow Rates Given by CFD Model with Measurements. (a) Scenario 1: CRAC Unit A Off/CRAC Unit B Operating, (b) Scenario 2: Both Units Operating

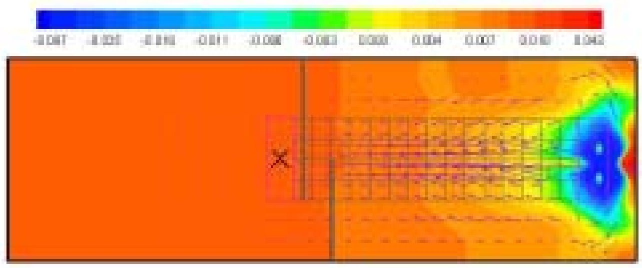

Figure 18. Velocity Vectors and Pressure Distribution (in wg) Under the Raised Floor for Scenario 1

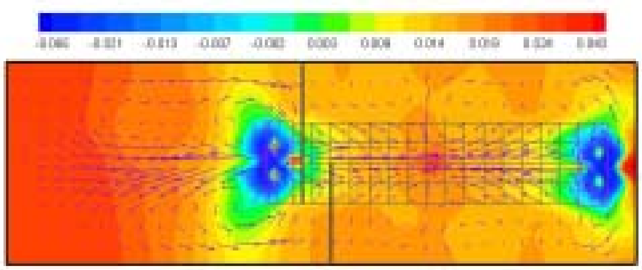

Figure 19. Velocity Vectors and Pressure Distribution (in wg) Under the Raised Floor for Scenario 2

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